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Effect of sintering atmosphere and carbon content on the densification and microstructure of laser-sintered M2 high-speed steel powder

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Abstract

In the present work, the role of graphite addition and sintering atmosphere on the laser sintering of M2 high-speed steel (HSS) powder was studied. The test specimens were produced using a continuous wave CO_2 laser beam at power of 200 W and at varying scan rate ranges from 50 to 175 mm s^{-1} under nitrogen and argon atmospheres. It was found that laser scan rate and sintering atmosphere strongly influence the densification of M2 HSS powder. Opposite to the conventional sintering that the sinterability of HSS is improved by graphite addition, the result of this work demonstrated that graphite addition decreases the sintered density of M2 HSS at relatively low laser scan rates, i.e. <100 mm s^{-1}, whilst at higher scan rates the effect is not very conspicuous. Furthermore, sintering under argon atmosphere yielded better densification compared to nitrogen atmosphere, particularly at higher scan rates. The microstructure of laser-sintered parts consisted of large and elongated pores and a heterogeneous metal matrix. The matrix structure includes martensite, high carbon austenite and inter-cellular or inter-dendrite carbide network. Addition of graphite to the M2 HSS powder increases the heterogeneity of the microstructure, as it was noticed from the variation in the micro-hardness throughout the sintered specimens.

Keywords: Direct metal laser sintering; M2 high-speed steel; Densification; Microstructure; Sintering atmosphere

1. Introduction

Manufacturing of functional prototypes and high performance artifacts using conventional methods such as machining usually is a time-consuming procedure and in a multi-step route. The demand for faster and less expensive product development has resulted in an impressive number of rapid prototyping (RP) processes being developed worldwide [1]. One could apply a relatively loose definition of rapid prototyping as “the fabrication of a physical, three-dimensional part of arbitrary shape directly from a numerical description, typically a CAD model, by a quick, highly automated and totally flexible manufacturing process” [2]. Most of the rapid prototyping techniques can produce high quality three-dimensional parts of varying degrees of complexity, size and shape by means of various photochemical, laser sintering, guided deposition, extrusion layering or sculpting processes [3]. One of the interesting applications of RP is rapid tooling, in which rapid production of tools using RP systems, either directly or indirectly is performed [4]. The aim is to reduce the cost and lead time required for the tooling phase in production cycle.

Among different available RP technologies, direct metal laser sintering (DMLS) exhibits a high potential for the net-shape fabrication of prototypes and short series tooling for plastic injection molding and die casting [5]. In this method, a focused laser beam is scanned across the surface of a loose powder bed, sintering and/or melting the powders into the shape of the required cross-section launched by CAD data. This enables the fabrication of complex shape parts without using conventional cost intensive shaping methods.

To date, much work has been performed to study the feasibility of producing intricate parts from different metal powders by the laser sintering method. Review about the fundamentals of the process and materials issue can be found in

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literature, for example, in [6–9]. Although recent advances in DMLS have improved the technology considerably, the method essentially relies on empirical, experimental knowledge and still lacks a strong theoretical basis [10]. This may be attributed to the complex nature of the process, which exhibits multiple modes of heat, mass and momentum transfer, and chemical reactions. Significant research and development are still required for the fabrication of high performance engineering parts with controlled microstructure.

In the present work, laser sintering of M2 high-speed steel (HSS) powder was investigated. The effects of sintering atmosphere and graphite addition on the densification and microstructure of the sintered parts were studied. High-speed steels are important engineering materials with a desired combination of wear resistance, hot hardness and toughness [11]. These steels are commonly used for applications that require strength and hardness combined with the ability to withstand high temperatures, e.g. cutting tools, and for demanding cold work applications such as fine blanking tools and dies [12]. Besides these important features, HSSs are high alloyed steels and exhibit complex carbide structures. Therefore, conventional processing of these materials, e.g. casting and hot working, gives rise to carbide coarsening at grain boundaries and a coarse grain microstructure. This reduces the toughness of steel, and consequently leads to premature failure at highly stresses condition [11]. Recently, the powder metallurgy route has been satisfactorily developed, allowing producing parts with improved properties and lower production costs than conventional methods [13–16]. The main advantage of this technique is the ability to obtain a fine and uniform microstructure in which segregation is reduced to insignificant levels [17–19]. Accordingly, better strength and grinding characteristics as well as higher hardness and resistance to wear can be achieved.

To date, considerable research effort has been reported on conventional sintering of high-speed steels. So far, it is known that the sinterability of these steels strongly depends on the chemical composition and sintering condition. Full densification can be obtained by supersolidus liquid phase sintering of HSS powder in vacuum [14]. In this context, the carbon content and sintering atmosphere play significant role, mainly because of their influence on the solidus temperature [20,21]. In the meantime, laser sintering of HSS powder has also attracted considerable attention regarding the process benefits in the fabrication of tool inserts directly from 3D CAD data. This rapid tooling method leads to compressed time to market solution, having huge impact on changing product design and test procedures [2,22]. Furthermore, similar to laser cladding, the cooling rate in DMLS is in the order of 10^4 K/s [8]. This implies additional advantages to provide fine grain structure with improved homogeneity of the resultant microstructure. Niu and Chang [23–25] have reported the possible mechanisms of particle bonding and the role of powder oxygen content during laser sintering of M3/2 HSS powder by scanning a continuous CO_2 laser beam over the surface of single-layer powder bed. Dewidar et al. [26] have shown that laser sintering of pre-alloyed HSSs is feasible, but bronze infiltration must be used to improve the mechanical properties of the components and thus allow for use in load-bearing applications. Akhtar et al. [27] have examined laser sintering and laser melting of HSSs. They have found that opposite to H13 tool steel, M2 HSS powder is not suitable for processing because of low attainable density (67% theoretical). In the previous work [28], it was shown that DMLS of M2 HSS powder is difficult but feasible if proper processing condition is used. Since the sinterability of this steel is strongly influenced by the carbon content and sintering atmosphere, within this work, the effects of graphite addition and processing under argon and nitrogen atmospheres are reported. The microstructure of laser-sintered parts is also addressed.

2. Experimental procedure

Gas atomized M2 high-speed powder (<50 μm, Osprey Co., UK) and fine graphite powder (2 μm, Aldrich, Germany) were used as starting materials. The chemical composition of the steel powder (in wt%) is as follows: Fe–0.86C–0.33Si–0.37Mn–1.25Cr–1.97V–5.23Mo–6.32W. In order to study the effect of carbon content, 0.4 wt% graphite was mixed with the M2 powder in a tumbling mixer for 30 min.

Rectangular test specimens with dimensions of 10 mm × 10 mm × 7 mm were produced using EOSINT M250X^{tended} laser sintering machine (Electro Optical Systems GmbH, Germany). The details of the instrument and the method of sample preparation were reported elsewhere [28,29]. The machine consists of a powder handling system, a continuous wave CO_2 laser with related optics and a process computer. The waist of the laser beam is around 0.2 mm. The process was performed under nitrogen and argon atmospheres. The working output power of 200 W, layer thickness of 0.1 mm and scan line spacing of 0.3 mm were applied. The laser scan rate was varied between 50 and 175 mm s^{-1}. The powder bed temperature was kept constant at 80 °C during processing.

After removing the sintered specimens from the build plate, the density of test parts was measured by volumetric method. Each processing condition was repeated at least two times and the result of the density measurement was expressed using the mean value. The standard deviation is less than 0.02 g/cm^3. The surfaces of the as-sintered samples were observed in a LEO 438VP scanning electron microscope (SEM). Microstructural evaluations were performed by both optical microscopy and SEM. Samples for metallographic examination were prepared using standard techniques and etched in 2% nital (2 ml HNO_3 per 100 ml CH_3OH). A Philips PW1800 diffractometer, equipped with a Ni chromotor and working with Cu lamp, was used for X-ray diffraction (XRD) examination. The micro-hardness of the test specimens was determined through Vickers method at load of 0.05 kg.